

Highlights from PHENIX - II

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Abstract.

This contribution highlights recent results from the PHENIX Collaboration at RHIC with emphasis on those obtained through lepton and photon measurements in PHENIX.

Submitted to: *J. Phys. G: Nucl. Phys.*

1. Introduction

Following the discovery of the surprising "perfect liquid" properties of the dense matter being produced in heavy ion collisions at RHIC [1], effort has intensified to quantify the detailed characteristics of that matter. Photons and leptons are of special interest because they are penetrating probes that do not undergo strong interactions and therefore are unlikely to interact with the dense matter after their production. Thus, they carry information about the system at the time of their production, throughout the entire evolution of the collision. The PHENIX experiment at RHIC was designed with emphasis on the measurement of leptons and photons, with electron and photon identification at mid-rapidity, and muon spectrometers at forward and backward rapidities (see [2] for a description of PHENIX).

As a result of their weaker electromagnetic coupling, lepton and photon production are rare processes that require large data samples for precise measurements. As a consequence of their low production rate the measurements are also subject to large backgrounds. In the case of directly radiated photons, the backgrounds are mostly photons from radiative decays of long-lived neutral mesons, predominantly the abundantly produced neutral pions. In the case of the electron measurement the background is mostly the internal or external conversion of these radiative decay photons into electron-positron pairs, and in the case of the muon measurements it is the weak decay of charged pions into muons.

With the 8th RHIC Run period recently completed, many of the new results reported by PHENIX are improved measurements of previously published results obtained from

‡ A list of members of the PHENIX Collaboration can be found at the end of this issue

the smaller data sets of the earlier RHIC runs. This is particularly true of the lepton and photon measurements. As an example, due to the factor of 10 increase in the PHENIX Run 4 data sample compared to Run 2, the measurement of the neutral pion spectra in Au+Au collisions has been extended to nearly 20 GeV/c transverse momentum with decreased statistical and systematic errors [3]. This directly translates into improved direct photon and non-photonic electron measurements.

2. Parton Energy Loss

One of the most exciting early results from RHIC was the observed strong suppression of neutral pion production in central Au+Au collisions [4] compared to expectations from scaled p+p collisions, and the lack of suppression of the direct photon yield [5]. This strongly supported the conclusion that the initial collisions occurred at the expected rate, as evidenced by the expected direct photon yield, but that the neutral pions were suppressed due to strong interactions and energy loss of the initially scattered parton as it traversed the dense medium prior to fragmentation into particles like the pion.

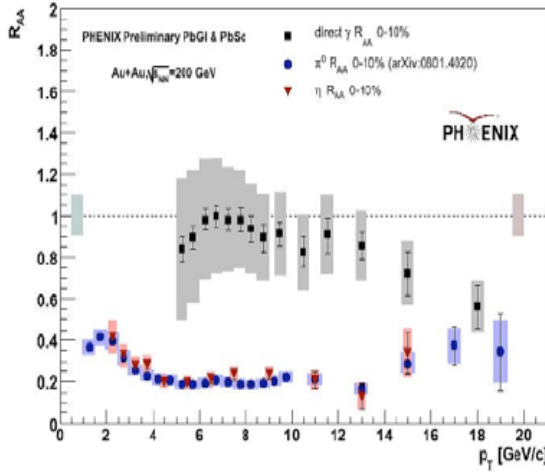


Figure 1. Nuclear modification factor R_{AA} for π^0 , η , and direct γ production as a function of transverse momentum for central Au+Au collisions.

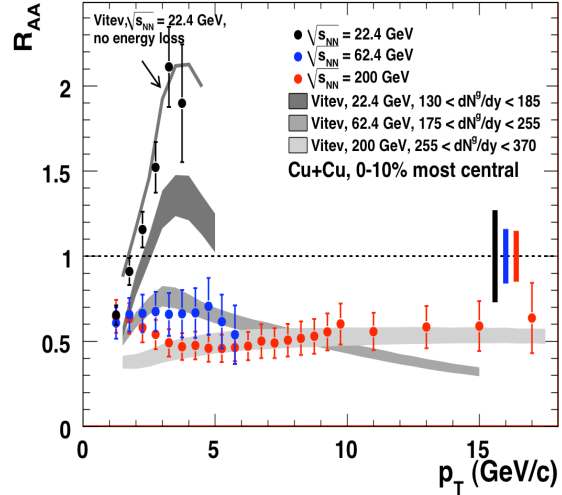


Figure 2. Nuclear modification factor R_{AA} for π^0 production in Cu+Cu collisions at $\sqrt{s_{NN}} = 22.4, 62.4$, and 200 GeV. The shaded regions are parton energy loss model predictions [7].

Nuclear effects are quantified in terms of the nuclear modification factor R_{AB} defined as $R_{AB} = (dN/dp_T|_{A+B}) / (\langle N_{coll} \rangle \times dN/dp_T|_{p+p})$ where $\langle N_{coll} \rangle$ is the average number of independent nucleon-nucleon collisions for the selected class of events. Final results from analysis of the Run 4 data set shown in Figure 1 demonstrate that the π^0 suppression, and η suppression as well, is consistent with being constant with transverse momentum over the region from 5 to 20 GeV/c [3].

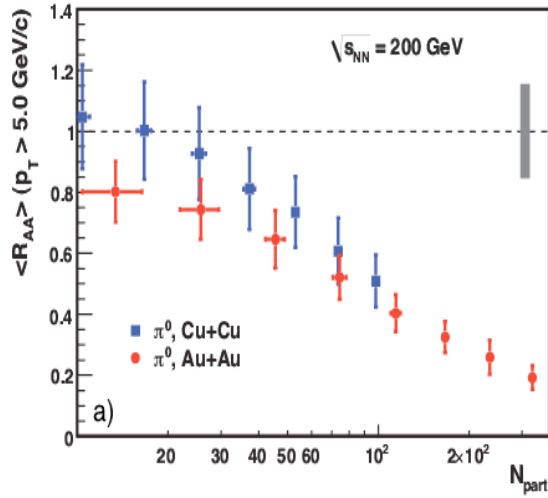


Figure 3. Nuclear modification factor R_{AA} for high $p_T \pi^0$ production as a function of the number of participant nucleons in Cu+Cu and Au+Au collisions.

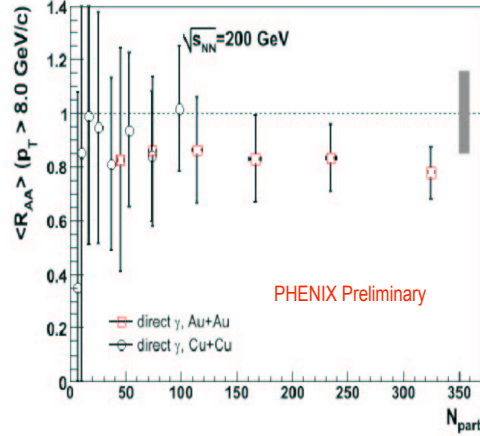


Figure 4. Nuclear modification factor R_{AA} for high p_T direct γ production as a function of the number of participant nucleons in Cu+Cu and Au+Au collisions.

52 New PHENIX results from Run 5 indicate that the neutral pion suppression is
 53 similar for Cu+Cu and Au+Au collisions for centrality selections with the same number
 54 of participating nucleons, as shown in Figure 3 [6]. On closer inspection, systematic
 55 differences between the Cu+Cu and Au+Au systems do appear at small participant
 56 numbers where differences in the geometry of the nuclear overlap may become important.

57 The dependence of the pion suppression on collision energy ($\sqrt{s_{NN}}$) has also been
 58 investigated with the Cu+Cu π^0 measurements where it is seen in Figure 2 that the
 59 suppression is quite similar at 200 and 62.4 GeV, but that the π^0 yield is instead
 60 enhanced compared to expectations from p+p collisions at 22.4 GeV, which indicates
 61 that suppression due to parton energy loss begins to dominate over Cronin enhancement
 62 between 22 and 62 GeV [6]. The $\sqrt{s_{NN}}$ dependence of the observed suppression is in
 63 good agreement with parton energy loss calculations [7].

64 As expected from previous observations, the high p_T direct photon yields are
 65 consistent within errors with no suppression for all centralities for both Cu+Cu and
 66 Au+Au collisions, as shown in Figure 4. The systematic study of the measured
 67 high p_T suppression of the single particle yields with varying particle species type
 68 (including heavy flavor), collision system centrality and $\sqrt{s_{NN}}$ will provide important
 69 input to model descriptions from which information about the opacity of the produced
 70 matter may be deduced by quantitative comparisons of the model predictions with the
 71 data [8, 9]. Beyond inclusive particle measurements, the parton energy loss is being
 72 further investigated through studies of high p_T direct photon v_2 measurements [10] and
 73 π^0 production as a function of the orientation with respect to the reaction plane [11],
 74 via two- and three-hadron correlations [2] as well as through γ -hadron correlations [12].

3. J/ψ Production

One of the earliest proposed signatures of the formation of dense deconfined matter (Quark Gluon Plasma) in relativistic heavy ion collisions was the predicted suppression of the J/ψ yield due to Debye screening of the $c\bar{c}$ quark bound state in the dense partonic matter [13]. Suppression of the J/ψ yield was soon afterwards observed in measurements at the CERN SPS [14]. New results from PHENIX [15] shown in Figure 5 indicate that the J/ψ suppression is the same for Cu+Cu and Au+Au collisions for centrality selections with the same number of participating nucleons [16]. The amount of suppression increases with the number of participating nucleons and surprisingly is rather similar at RHIC and SPS energies [17]. Also, contrary to expectations from Debye screening alone, the suppression is observed to be stronger at forward rapidity than at mid-rapidity (Figure 5).

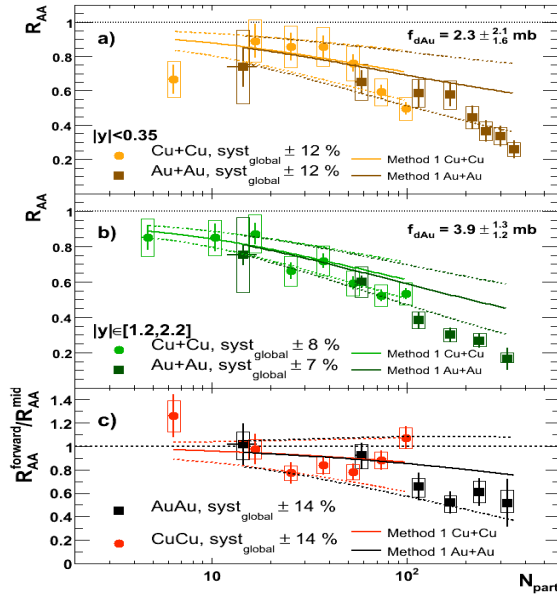


Figure 5. Nuclear modification factor R_{AA} as a function of the number of participant nucleons for Au+Au and Cu+Cu collisions at a) mid-rapidity and b) forward rapidity, and c) ratio.

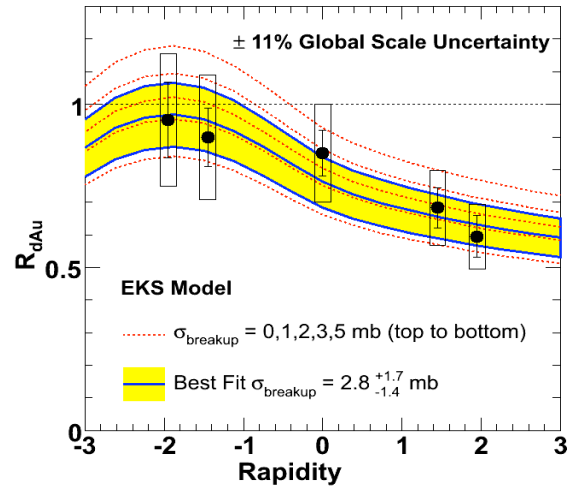


Figure 6. Nuclear modification factor R_{dAu} as a function of rapidity for J/ψ production in d+Au collisions compared to EKS model calculations [18].

At SPS energies the J/ψ yield is suppressed also in p+A collisions. This is interpreted as a cold nuclear matter (CNM) effect as a result of modification of the nucleon parton momentum distributions in the nucleus and the breakup of the J/ψ due to its interaction with the cold spectator nucleons. PHENIX has investigated the cold nuclear matter effects on J/ψ suppression at RHIC energies using d+Au collisions, with comparison to p+p collisions. A new analysis was recently completed using the Run 5 p+p data set, which is a factor of 10 larger than the Run 3 p+p data set, together with the Run 3 d+Au data set. An improved analysis with better understanding of detector

effects has been applied consistently to both data sets. As shown in Figure 6 the new result on the d+Au nuclear modification factor R_{dAu} still has a rather large uncertainty that prevents to draw firm quantitative statements on any additional suppression in Au+Au collisions beyond cold nuclear matter effects (see Figure 5) [19, 20]. With the PHENIX Run 8 d+Au data sample just obtained it is estimated that the number of J/ψ 's accumulated is a factor of 50 greater than for Run 3, which should allow to constrain the contribution from cold nuclear matter effects more strongly.

4. Heavy Flavor

First measurements on heavy flavor quark production in PHENIX via single electron measurements provided another surprising result at RHIC [21]. Although it was expected that heavy quarks should show less stopping than light quarks in dense partonic matter, and hence heavy quark jets should show less quenching, it was instead observed that the yield of electrons from heavy flavor at high transverse momentum was suppressed in Au+Au collisions with nearly the same suppression as observed for π^0 's. In addition, single electrons attributed to heavy flavor were observed to show large azimuthal asymmetries [21], with the single electron v_2 results recently extended to higher transverse momenta with the Run 7 Au+Au data set, as shown in Figure 7. Taken together, the results implied significant damping of the motion of heavy quarks as they propagate through the dense matter produced at RHIC. Together with model calculations these observations allow to extract information on the viscosity to entropy ratio, η/s , of the dense matter and draw the conclusion that the matter has an η/s ratio close to the conjectured lower bound of $\sim 1/4\pi$, essentially a "perfect liquid" [1, 22].

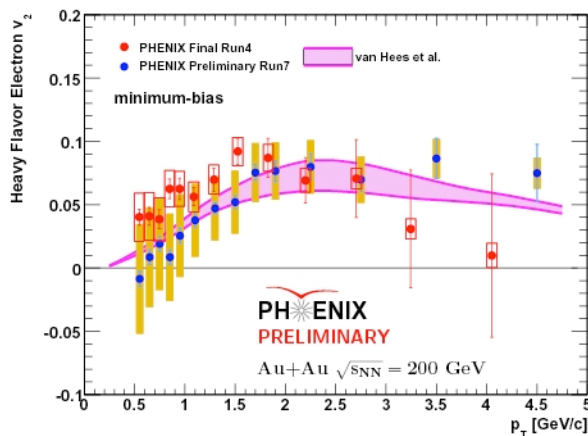


Figure 7. Azimuthal anisotropy parameter v_2 of heavy flavor electrons in minimum bias Au+Au collisions from Run 4 [21] and new preliminary results from Run 7 compared to transport calculations by van Hees [23].

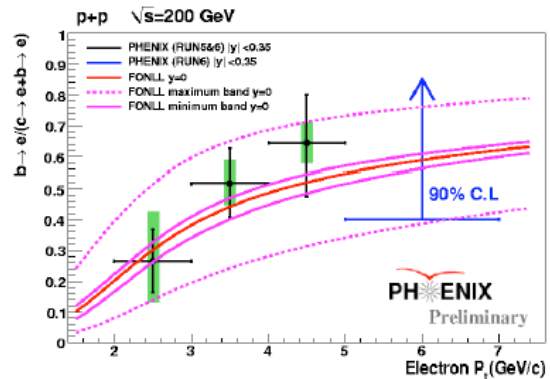


Figure 8. Ratio of electrons from bottom to electrons from charm compared to FONLL calculations [24].

With the goal to better separate the charm and bottom contributions (and shed light on the unresolved discrepancies between the STAR and PHENIX charm results) PHENIX has performed single muon measurements at forward rapidities in p+p collisions to extract information on the rapidity dependence of the heavy flavor production [25]. Also, electron-hadron correlation measurements have been used to perform a pseudo- D^0 analysis to explicitly separate the charm and bottom contributions [26] in p+p collisions with results shown in Figure 8. The measured ratio is found to be in good agreement with FONLL calculations, although separately the charm and bottom measurement each disagree significantly with the FONLL calculations [26].

5. Low Mass Electron Pairs

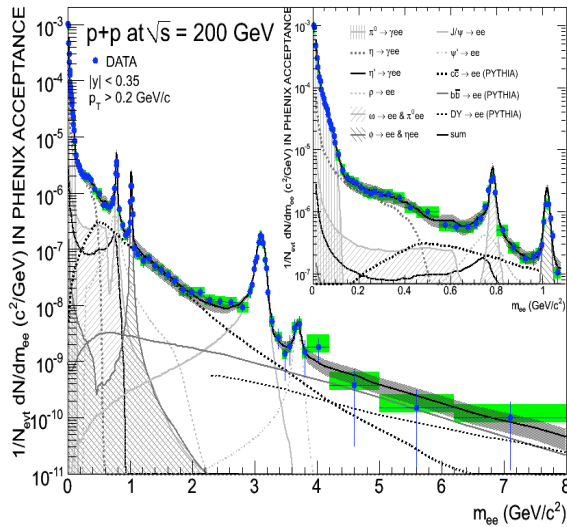


Figure 9. The yield of e^+e^- pairs per p+p collision compared to the yield expected from hadronic decays. Statistical (bars) and systematic (boxes) uncertainties are shown separately.

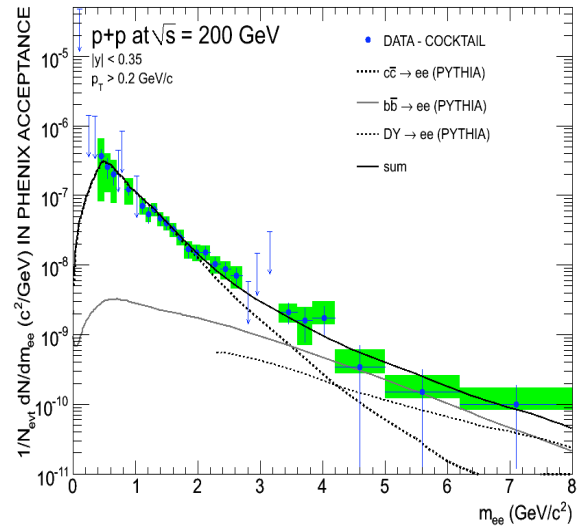


Figure 10. The yield of e^+e^- pairs after subtraction of the contribution of hadronic decays.

The measurement of electron-positron pairs allows the study of direct virtual photon production with the advantage that the main background from neutral pion decays (due to internal or external photon conversion) is about two orders of magnitude smaller than for the measurement of real direct photons. An additional order of magnitude reduction of the background to the virtual photon measurement can be obtained by using pairs with mass above the pion mass. The e^+e^- pair mass spectrum for p+p collisions at 200 GeV from the PHENIX Run 5 data set [27] is shown in Figure 9. It is seen to be in very good agreement with the expected yield based on a Monte Carlo calculation of the electron-pair yield from hadron decays using measured hadron yields, together with contributions to the e^+e^- mass spectrum from Drell-Yan, $c\bar{c}$, and $b\bar{b}$ decays as predicted

by the PYTHIA model. Figure 10 shows the measured e^+e^- mass spectrum, after subtraction of the hadronic decay contribution, compared separately to the PYTHIA model predictions to demonstrate the good agreement of the measurement with the predicted $c\bar{c}$ and $b\bar{b}$ contributions.

In the case of Au+Au collisions, the e^+e^- mass spectrum shows a very large excess beyond expectations from hadronic decays in the low mass region between the π^0 and ω meson masses, as shown in Figure 11 [28]. This excess is dominantly at transverse momenta below about 1 GeV/c, indicating that it is produced in the cooler late hadronic phase of the collision.

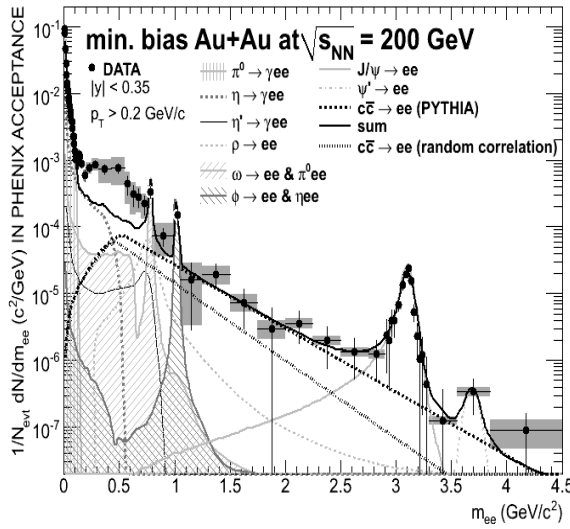


Figure 11. Invariant yield of e^+e^- pairs in minimum bias Au+Au collisions compared to the yield expected from hadronic decays. Statistical (bars) and systematic (boxes) uncertainties are shown separately.

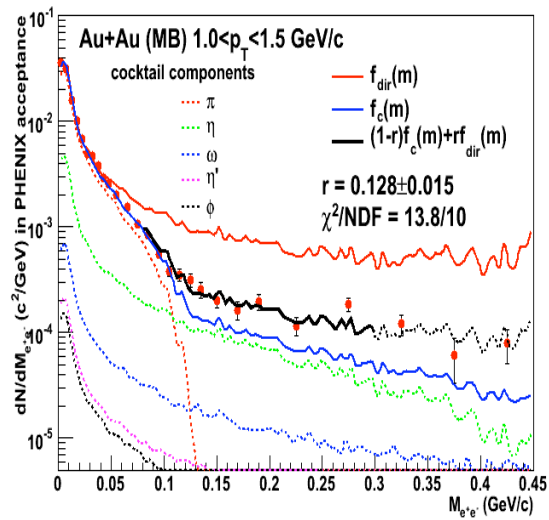


Figure 12. Invariant yield of low mass e^+e^- pairs with $1.0 < p_T < 1.5$ GeV/c in minimum bias Au+Au collisions. The solid blue curve indicates the expectation with the measured η Dalitz contribution.

However, a significant e^+e^- excess also persists at higher transverse momenta in the e^+e^- mass region above the π^0 mass, as seen in Figure 12. This excess can be used to extract the virtual photon momentum spectrum with an error significantly smaller, in the low transverse momentum region, than obtained by measurement of real photons [5, 29, 30, 31]. A small but significant excess is also observed in p+p collisions in the mass region above the π^0 mass at transverse momenta above 1 GeV/c. As shown in Figure 13, the measured invariant photon yield for p+p collisions by the virtual photon measurement is found to be consistent with expectations from pQCD predictions.

On the other hand, for Au+Au collisions, the virtual photon yield associated with the observed e^+e^- excess is greater than that expected from the p+p measurement, which suggests that it is due to thermal radiation from the early phase of the Au+Au

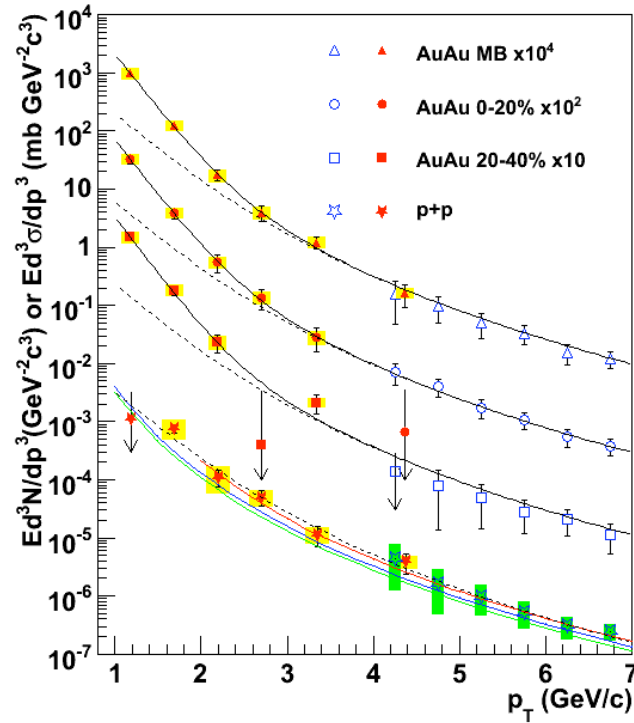


Figure 13. Invariant cross section of direct photons in p+p collisions and Au+Au collisions for several centrality selections compared to scaled NLO pQCD predictions (dashed curves). The open points are previously published PHENIX results [5, 29].

collision. These measurements hold promise that the thermal photon spectrum may finally be extracted with sufficient precision to provide significant constraints on the initial temperature of the dense matter being created at RHIC [30, 31, 32].

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